The Dynamic Extreme Universe in X-rays (DEUS-X) TDAMM Machine

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on behalf of

Members of the X-ray Timing Science Analysis Group

(Co-Chairs: Tom Maccarone, Krista Lynne Smith, Riccardo Arcodia)

Key science-enabling capabilities

- “Gap free” sky and temporal coverage — for X-ray transient discovery and follow-up monitoring
- Rapid response and slew — on target in minutes
- Broadband/multiwavelength — simultaneous correlative studies.
- High dynamic range in X-ray flux — 5–6 orders of magnitude
- High-resolution, absolute timing — sub-μsec, traceable to UTC
- Good spectral resolution — 50–200 eV (CCD-like or better)

Adopt proven, mature technologies for affordability and early implementation

- *DEUS-X builds on STROBE-X Probe concept, well-studied and highly rated (Category I), plus Swift’s multiwavelength model.*

Dynamic Extreme Universe in X-rays (DEUS-X)

A two-fleet system for transient discovery & responsive follow-up

Wide-field discovery. Fill the "X-ray gap" in sky surveys with multiple spacecraft *(polar orbit)* for near-all-sky, uninterrupted transient discovery and ~1' localization

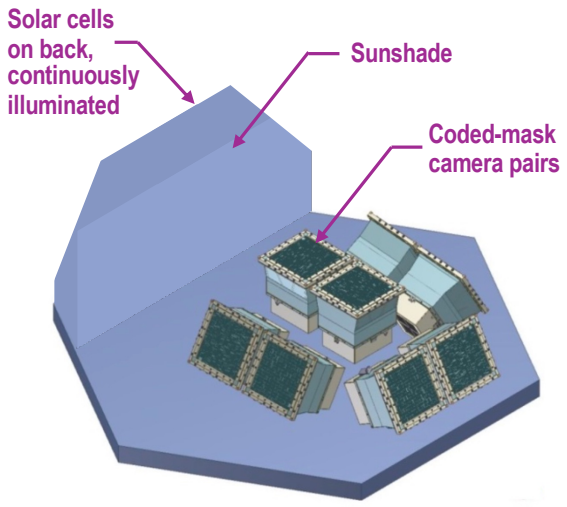
Rapid response to triggers. High cadence, multi-target follow-up with agile satellites *(equatorial orbit)* that leverage commercial-space offerings

- **Broadband, large area spectral timing.** Multi-m^2 soft and hard X-ray pointed instruments with sub-μs timing and good spectral resolution
- **X-ray imaging.** With < 10" resolution and ~600 cm^2 for arcsec localization and background/context
- **Multi-wavelength follow-up.** Co-aligned UV/Opt/IR telescope with smaller FoV but more simultaneous filters compared to *Swift*/UVOT
- **Polarimetry potential.** For > 10 keV X-rays, leveraging, e.g., novel fine-pitch strip detectors or high-resolution CCDs.

DEUS-X, the wide-field discovery machine

A fleet of ≥ 3 nadir-pointed spacecraft in Sun-synchronous orbit (SSO) provides *uninterrupted coverage of* 3.5π *sr of sky* away from the Sun in 2–50 keV X-rays.

STROBE-X Wide-Field Monitor (as baseline/example)



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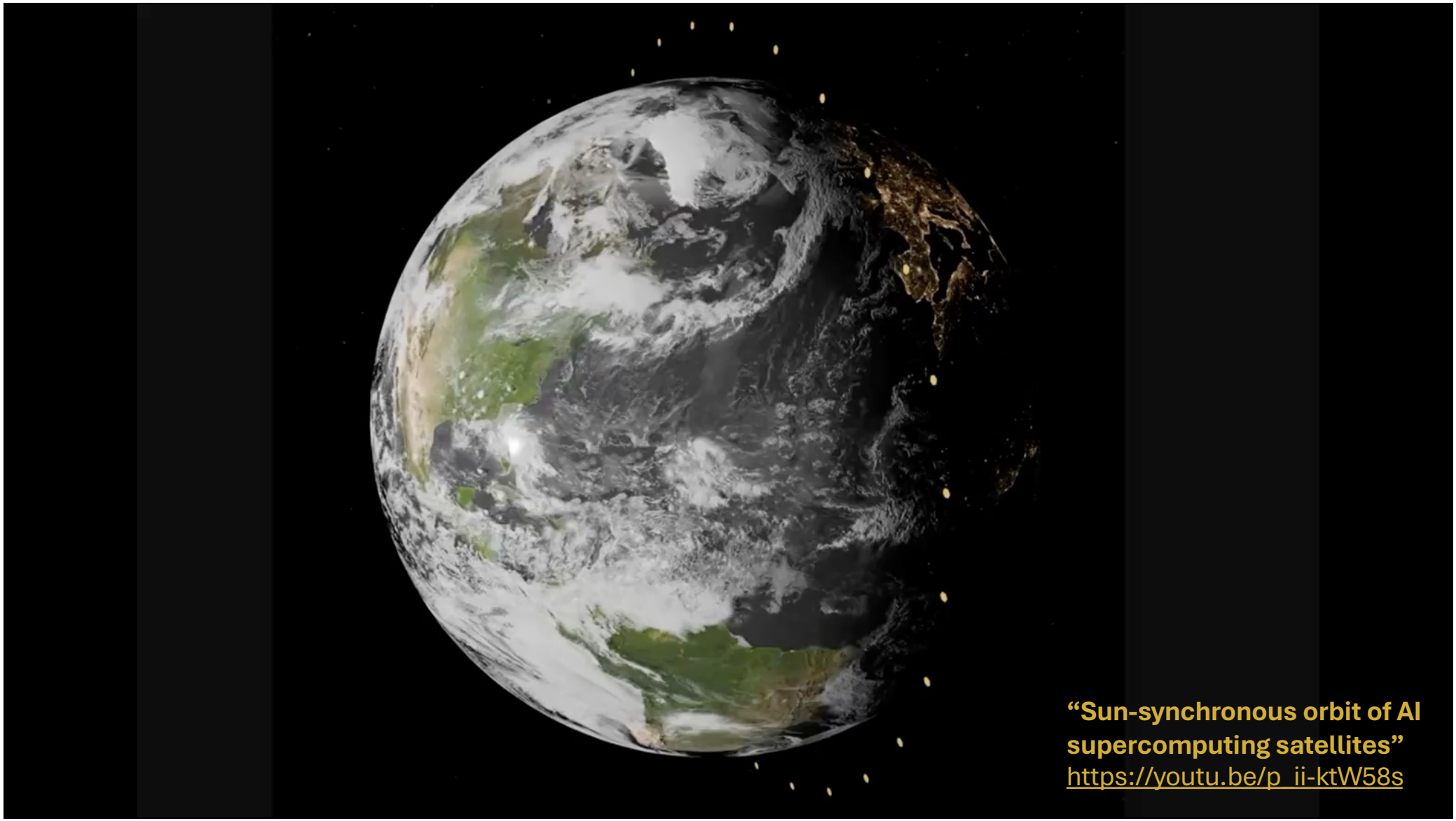

“Sun-synchronous orbit of AI supercomputing satellites”
https://youtu.be/p_ii-ktW58s

Why SSO? Advantages and potential drawbacks

Advantages

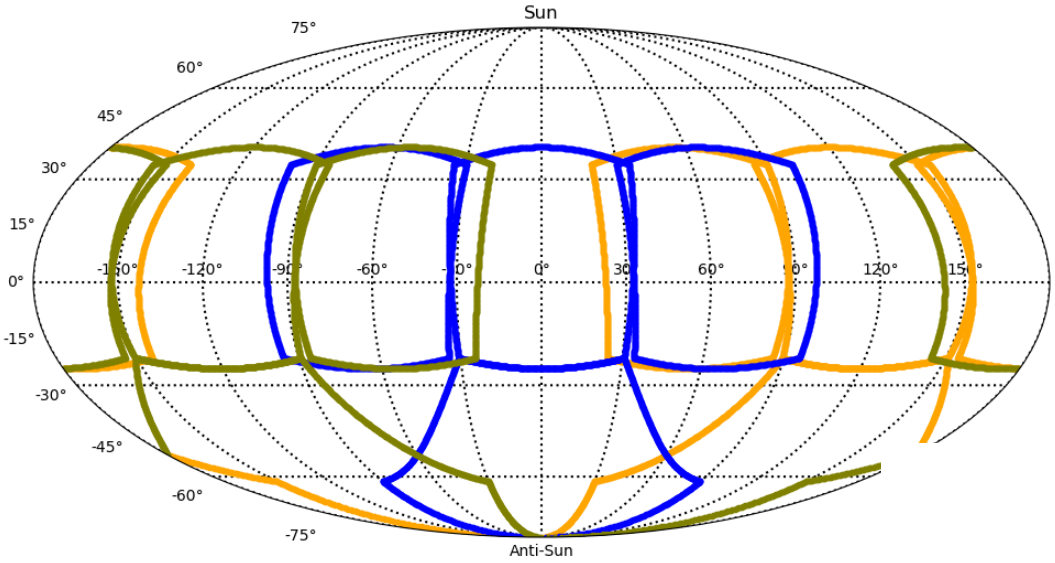
- **Full, continuous sky coverage**
- Minimizes spacecraft engineering complexity — key to **affordability** of multi-vehicle mission
  - Straightforward thermal, electrical, mechanical designs: orientations of radiators & solar panels are fixed (no need for moving parts), and simplified operations
  - Nadir-pointing attitude control well established for polar orbits
  - Overall size & shape fit well together in a single launch-vehicle fairing.

Sun-Earth Lagrange points are also naturally Sun-synchronous

Drawbacks — but…

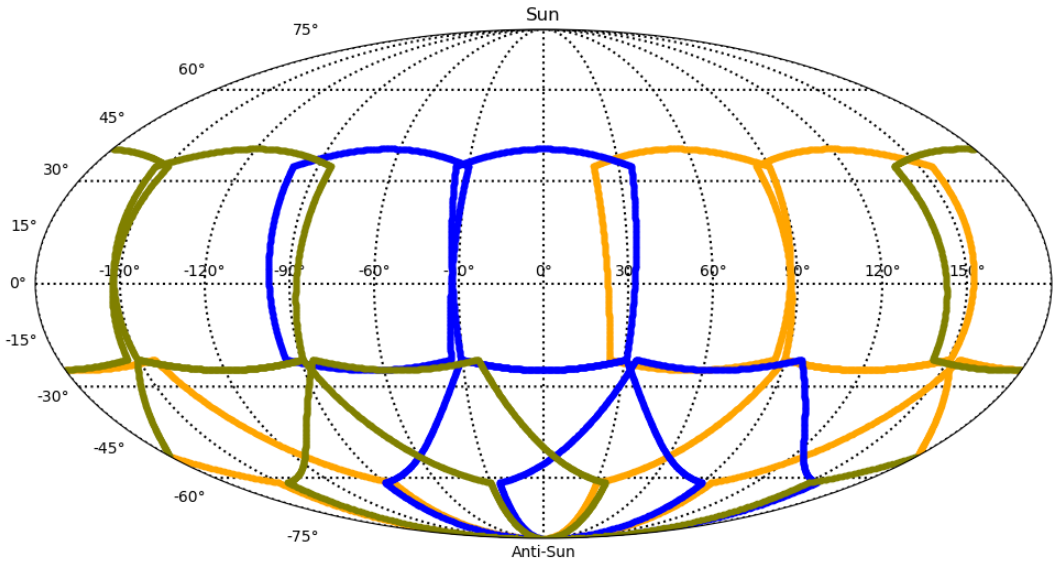
- Competition for SSO (from AI data centers in space??) — but…
  - Could mean **rideshare opportunities**
  - Good comm infrastructure
  - Most Earth-observing SSO missions have stringent illumination requirements; we can accept less-sought-after SSO orbits
- Higher, more variable particle radiation in polar orbit — but…
  - Can enhance shielding, including magnetic to deflect charged particles
  - Background will not affect all s/c simultaneously; with overlapping FOVs, transients can be captured by another vehicle.

Gap-free, continuous sky coverage



Olive, **blue**, **orange** outlines show FoVs, at 50% coding, for 3 spacecraft 120º apart in the same SSO, each with 4 camera pairs. The “equator” is the plane normal to the Sun-Earth line.

Left: Sky coverage for the STROBE-X WFM layout: significant overlap from adjacent cameras, but gaps around ±60º longitude.

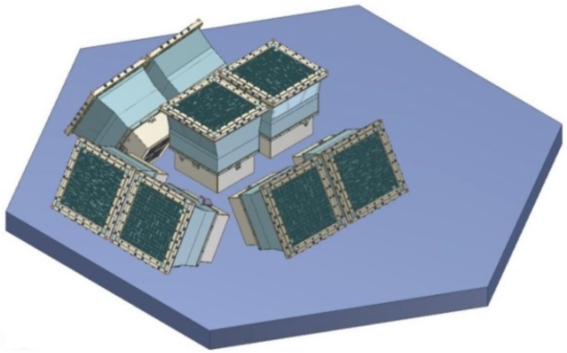


Right: Camera config that eliminates the gaps, for uninterrupted coverage >~ 50º from the Sun at 50% coding.

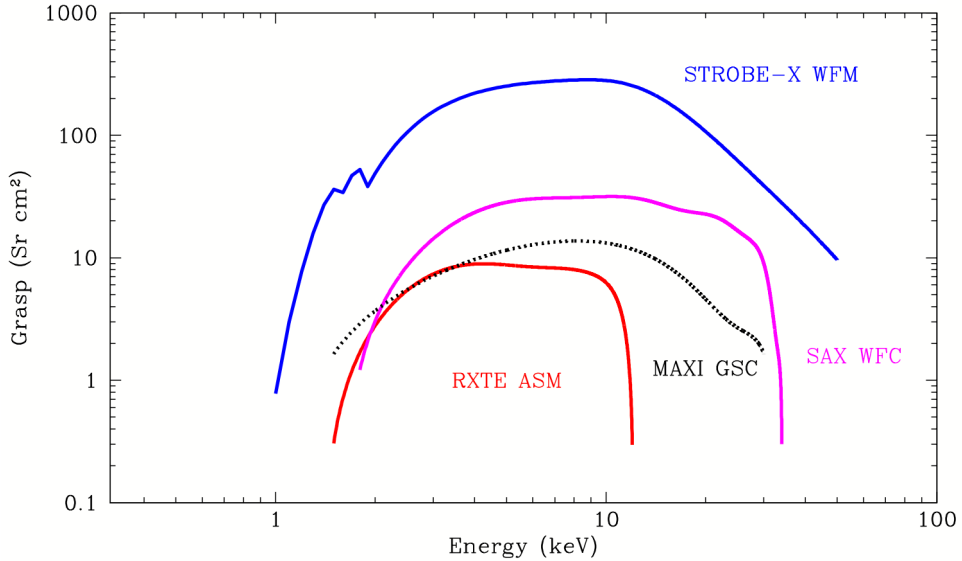
All FoVs progress horizontally as the satellites circle Earth 12–16 times per day. Seasonally, the anti-Sun direction sweeps the ecliptic plane.

An illustrative example of capability *within reach now*

STROBE-X WFM
Each camera 37×37×36 cm
Total mass: 216 kg
FoV: 65° x 65° full width
(50% coding)



Grasp of a single WFM (on a single spacecraft)



WFM Performance Specifications	
Quantity	**Value (CBE)**
Bandpass	2-50 keV
Collecting Area @ 8.5 keV	364 cm^2
Count Rate on 1 Crab	380 c/s
Background Rate	480 c/s/camera
Sensitivity (5 sigma) in 1 day	4 mCrab
Sensitivity (5 sigma) in 1 s	920 mCrab
Timing Resolution	24 μs
Energy Resolution @ 6 keV	300 eV
Max Source Flux	100 Crab
Transient localization to ~1'	<15 s

But what about radiation?

- Data loss countered with overlapping FoVs and/or additional spacecraft
- Damage to instrument mitigated with passive and magnetic shielding
- Intrinsically rad-hard technologies are potentially game-changing — e.g., silicon carbide (SiC) is a demonstrated position-sensitive, low-noise, photon-counting X-ray detector, with rad-hard UV-photodiode heritage in space
  - Needed SiC advances: thickness (100s rather than 10s of μm) and area (10s of cm^2).

Silicon Carbide Microstrip Radiation Detectors

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REVIEW article

Front. Phys., 11 October 2022

Sec. Radiation Detectors and Imaging

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SiC detectors: A review on the use of silicon carbide as radiation detection material

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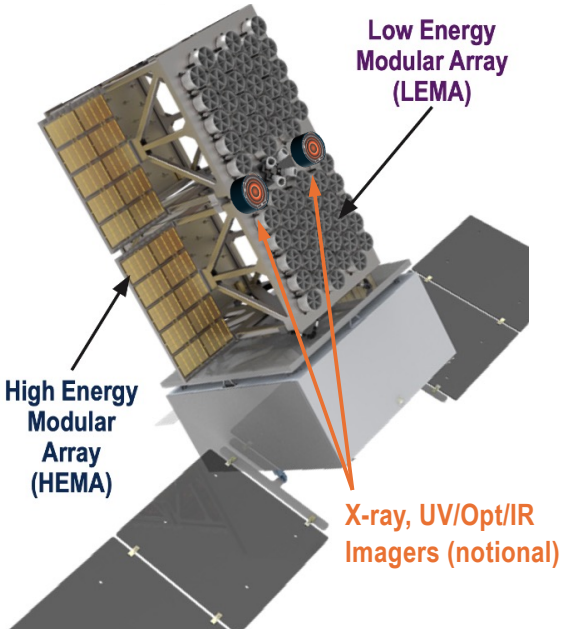
DEUS-X, the rapid follow-up machine

Three agile spacecraft in equatorial orbit provide *prompt multi-wavelength* follow-up of transients, as well as high-cadence monitoring of evolving sources, for *multiple targets simultaneously*

STROBE-X (baseline) pointed instruments + multi-wavelength



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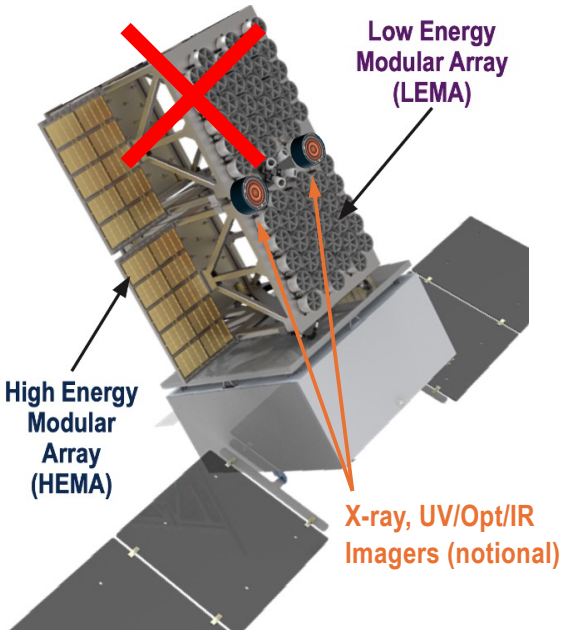
DEUS-X, the rapid follow-up machine

STROBE-X (baseline) pointed instruments + multi-wavelength



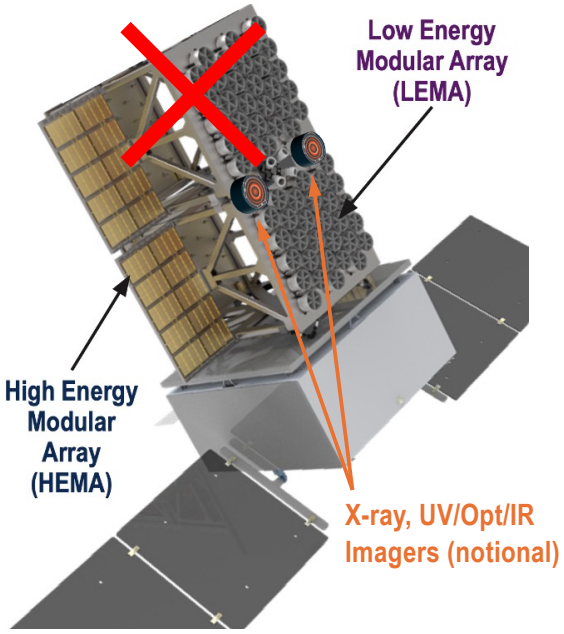
Three agile spacecraft in equatorial orbit provide *prompt multi-wavelength* follow-up of transients, as well as high-cadence monitoring of evolving sources, for *multiple targets simultaneously*

3–4 spacecraft could each host ½ of the proposed HEMA and LEMA
➔ 1.5–2x their collecting area in total

eed: 0.00000 m/s

DEUS-X, the TDAMM machine

STROBE-X (baseline) pointed instruments + multi-wavelength



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3–4 spacecraft could each host ½ of the proposed HEMA and LEMA
➔ 1.5–2x their collecting area in total

eed: 0.00000 m/s

An illustrative example of capability *within reach now*

LEMA Performance Specifications	
Quantity	**Value (CBE)**
Bandpass	0.2-12 keV
Collecting Area @ 1.5 keV	16,000 cm^2
Non-Imaging FoV	
Count Rate on 1 Crab	
Background Level	6×10^{-13} $erg/cm^2/s$
Sensitivity (5-sigma in 1 ks Crab-like spectrum)	1.5×10^{-13} $erg/cm^2/s$
Timing Resolution	40 ns
Absolute Time Accuracy (to UTC)	200 ns
Energy Resolution @ 1keV	85 eV
Max Source Flux	15 Crab

x1.5 for 3 s/c
⇒ **2.4 m^2**

LEMA mass: 1,238 kg

HEMA Performance Specifications	
Quantity	**Value (CBE)**
Bandpass	2-30 keV
Collecting Area @ 8.5 keV	34,000 cm^2
Non-Imaging FoV	
Count Rate on 1 Crab	
Background Rate	548 c/s (5 mcrab)
Sensitivity (5σ in 1 ks)	2×10^{-12} $erg/cm^2/s$
Timing Resolution	2 μs
Absolute Time Accuracy (to UTC)	7 μs
Energy Resolution @ 6 keV	<300 eV (<500 eV in eFOR)
Max Source Flux	15 Crab

x1.5 for 3 s/c
⇒ **5.1 m^2**

HEMA mass: 743 kg

Multiwavelength context — additional follow-up instruments

With ~1’ discovery localization, pointed instruments don’t need wide FoVs, simplifying design and lowering cost

- **X-ray imager** → arcsec localization & background knowledge for non-imaging instruments
  - Progress toward sub-10’’ resolution IXPE-like mirrors — SuperHERO (balloon) and FOXSI (sounding rocket)
  - Shorter focal length (3 m LEMA vs. 4 m IXPE), but no extendable boom needed to get A_{eff} ~ 300 cm^2 per spacecraft at lower cost and risk
  - Enhanced high-energy response with coated optics; can be coupled with imaging detectors up to ~20 keV (e.g., Abe Falcone’s hybrid CMOS devices).
- **UV/Opt/IR telescopes** → simultaneous multi-band time-domain correlation
  - Even with similar size to *Swift* UVOT, can improve performance with better sensors and dichroic filters down to J/H band in IR
  - Registering images to IR stars can simplify pointing requirements, lower s/c cost.

Realize cost savings by implementing capabilities where they are “easy,” relaxing performance requirements elsewhere.

Questions that motivate a study

- Focusing on affordability, what simplifications, common elements, modularity, etc., help enable a fleet? Do “economies of scale” matter?
- Can these fleets be launched efficiently — e.g., rideshare or single LV each? How best to leverage mass-produced commercial busses?
- Strategy for wide-field monitor — Coded-mask vs. lobster-eye? Orbit? Detector? Add GRB capability?
- How best to distribute follow-up instruments across spacecraft? What are the driving considerations?
- LEMA with multilayer coatings + thicker detectors — how effective compared to dedicated hard-band instrument (collimated or focused)?
- Are SDDs still the best detector choice? What would it take to extend passband to >~ 100 keV? Can high-resolution spectroscopy and/or polarimetry be done cost-effectively?

The promise & potential of DEUS-X

X-ray transient alerts from wide-field cameras, and external multi-messenger facilities, are communicated to a multiwavelength follow-up fleet within minutes

Only a follow-up fleet capable of targeting multiple objects at a time can keep up with the anticipated flood of transient triggers, while at the same time monitoring multi-wavelength source evolution and accumulating deep exposures

Like NICER and Swift, DEUS-X engages multiple (~10 per orbit!) science programs concurrently.

DEUS-X finally provides dynamic observing capability to match the dynamic multi-messenger sky, beyond the reach of single-vehicle missions.

Backup slides

"*Highest priority sustaining activity is a space-based time-domain and multi-messenger program of small and medium-scale missions.*"

Astro2020 report

An **ideal TDAMM mission** is…

- Sustaining activity → … a discovery engine
- Multi-messenger → … responsive to triggers from anywhere, anytime
- Time domain → … able to track source evolution on all timescales
- Small and medium-scale → … nimble, scalable, affordable
- Highest priority → … to be done as soon as possible!

An illustrative example of capability *within reach now*

LEMA Performance Specifications	
Quantity	**Value (CBE)**
Bandpass	0.2-12 keV
Collecting Area @ 1.5 keV	16,000 cm^2
Non-Imaging FoV	4 arcmin (FWHM)
Count Rate on 1 Crab	111,000 c/s
Background Level	6×10^{-13} $erg/cm^2/s$
Sensitivity (5-sigma in 1 ks Crab-like spectrum)	1.5×10^{-13} $erg/cm^2/s$
Timing Resolution	40 ns
Absolute Time Accuracy (to UTC)	200 ns
Energy Resolution @ 1keV	85 eV
Max Source Flux	15 Crab

LEMA mass: 1,238 kg

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Bandpass	2-30 keV
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Non-Imaging FoV	1° FWHM
Count Rate on 1 Crab	104,000 c/s
Background Rate	548 c/s (5 mcrab)
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Timing Resolution	2 μs
Absolute Time Accuracy (to UTC)	7 μs
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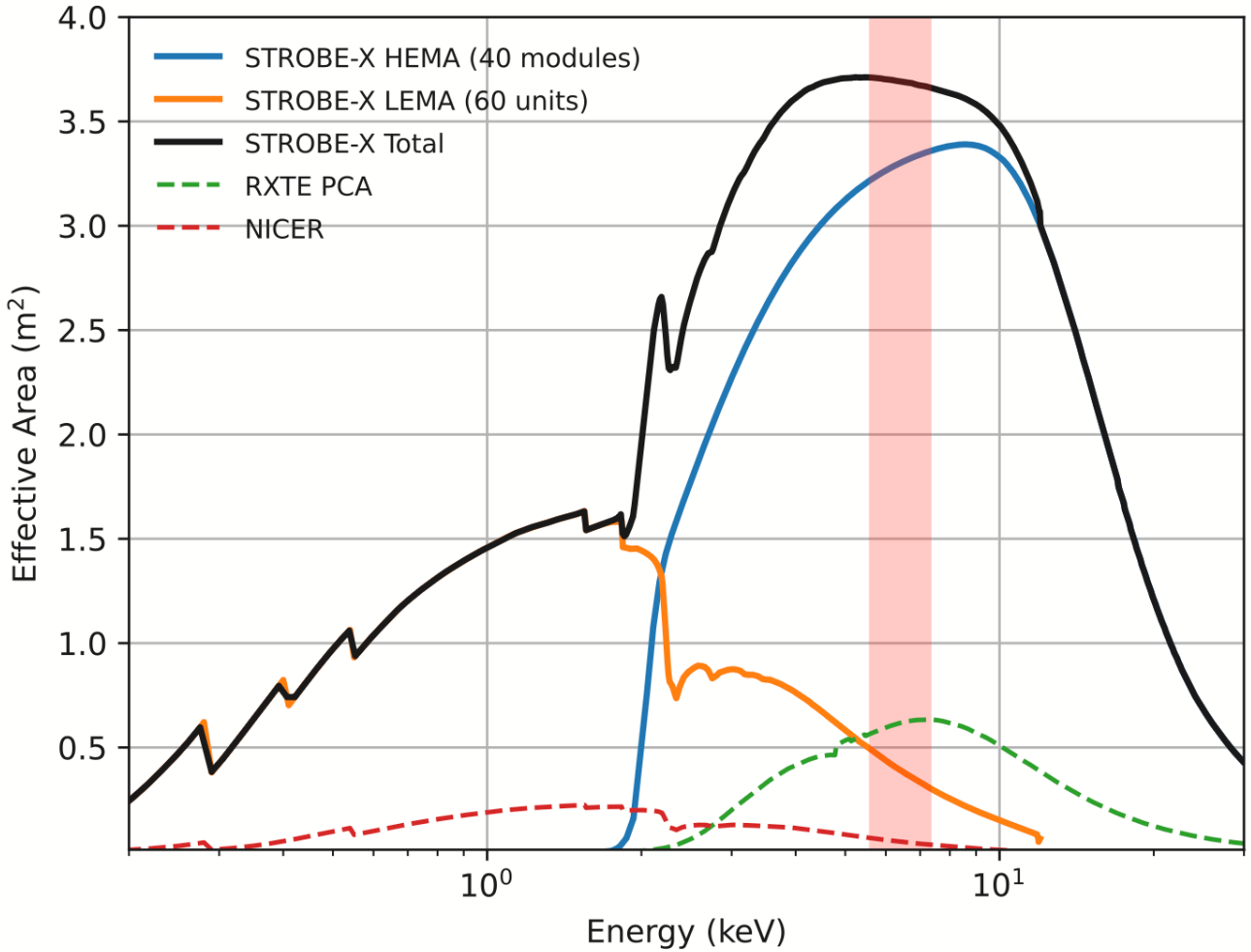

As proposed, **before 1.5–2x increase** by distributing modules across 3–4 spacecraft

Also, LEMA area above 2.5 keV increases with multilayer-coated optics and thicker detectors (available now).